

# Actually Measuring $k_T$ at an EIC

Mark D. Baker\*

MDBPADS LLC / BNL

Elke C. Aschenauer

BNL

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\* [mdbaker@mdbpads.com](mailto:mdbaker@mdbpads.com) or [mdbaker@bnl.gov](mailto:mdbaker@bnl.gov)

# ... Looking for El Dorado: The Lost **Golden** Measurement

M.D. Baker

E.C.Aschenauer



08 January 2016

# Plan / Summary

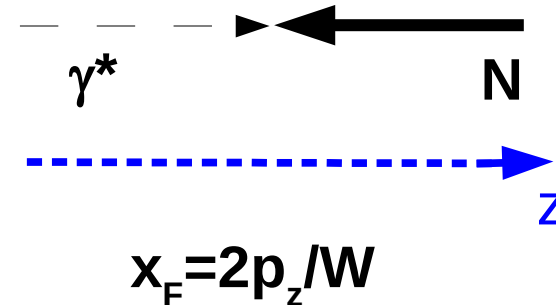
- Recap: Intrinsic  $k_T$  from beam remnant jet recoil
- Published ZEUS data: 2 surprises!
  - 1: **We can actually measure  $k_T$  using ZEUS data.**
  - 2: Energy dependence not quite as expected.
- Anything left for EIC to do? (YES!)

# Direct measurement of intrinsic $k_T$

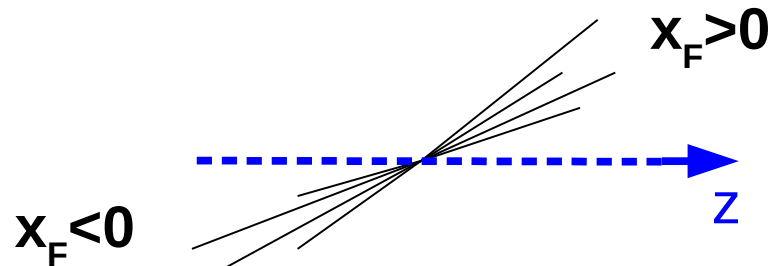


Consider the hadronic center of mass (HCMS) frame

$\gamma^*N$  frame (for ep)

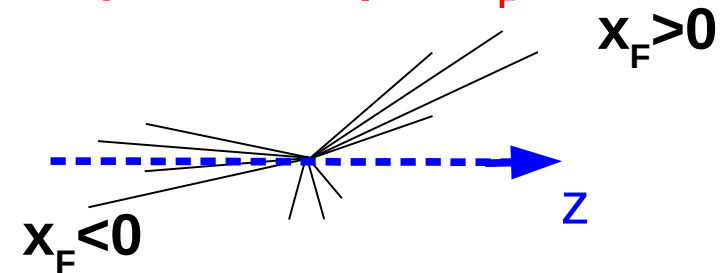


Intrinsic  $k_T$  at high  $|x_F|$ .

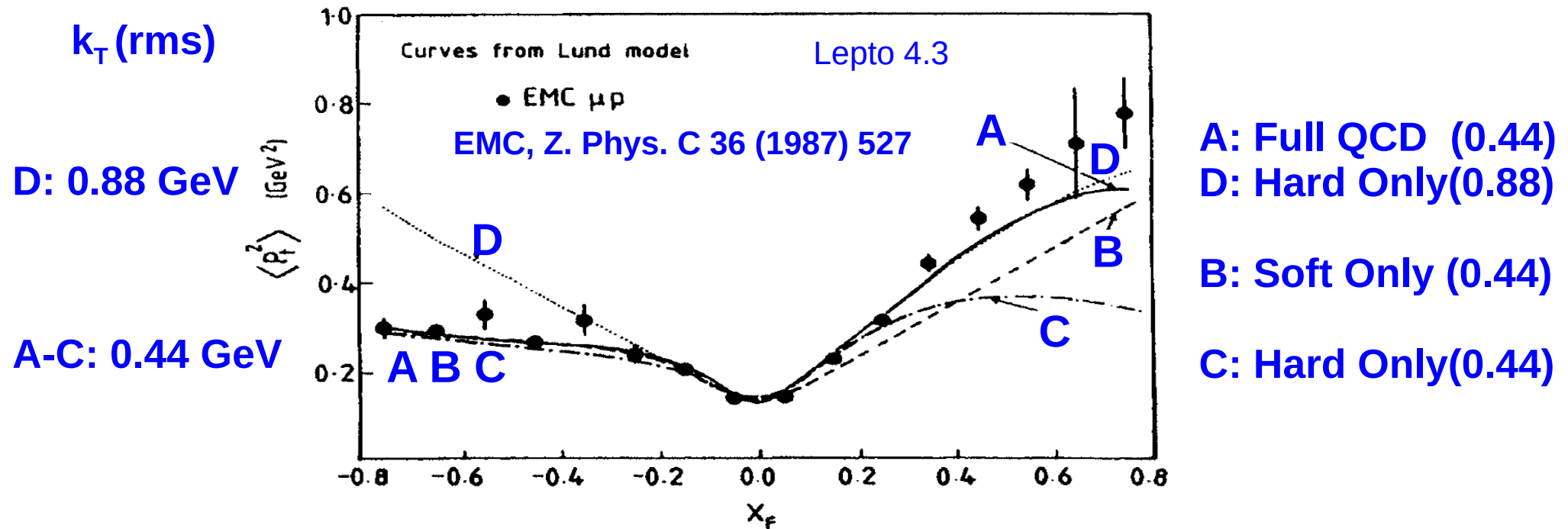


QCD radiation with  $k_T=0$  primarily shows up at  $x_F \geq 0$

HCMS frame

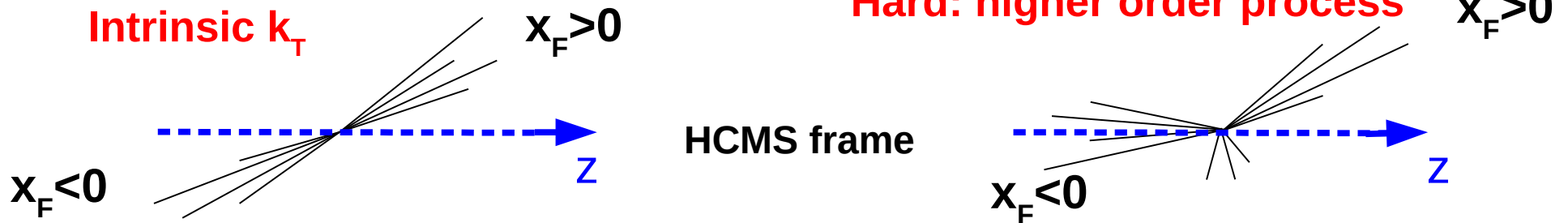


# “Seagull” measures intrinsic $k_T$



$z$

QCD: Soft: Parton Shower  
Hard: higher order process



# The switch to “effective” $k_T$

E665, H1 & ZEUS did not use the **golden method**, so it was lost!

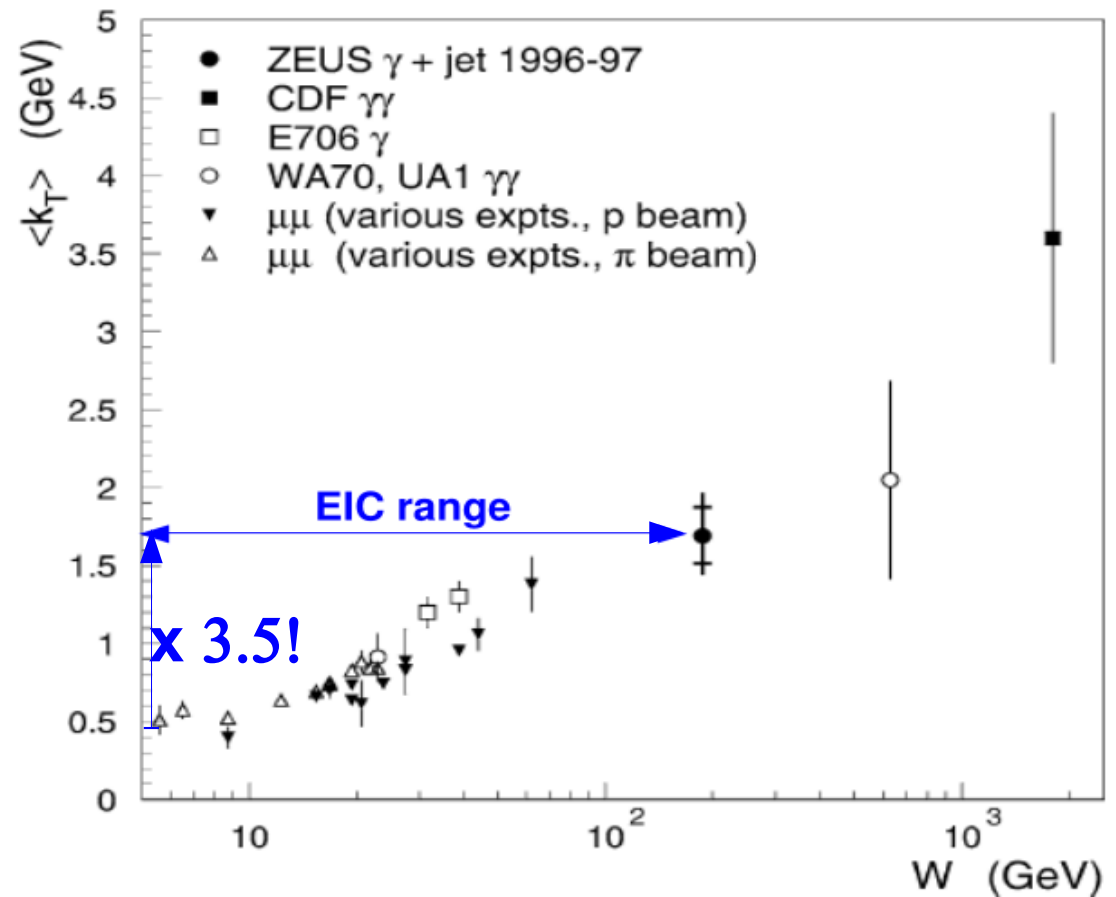
“Effective”  $k_T$  measured w/o target jet recoil varies a **LOT!**

In order to relate  $k_T$  to fundamentals like  $Q_s$ , we must actually measure  $k_T$

[Pythia 6.4 manual hep-ph/0603175](#)

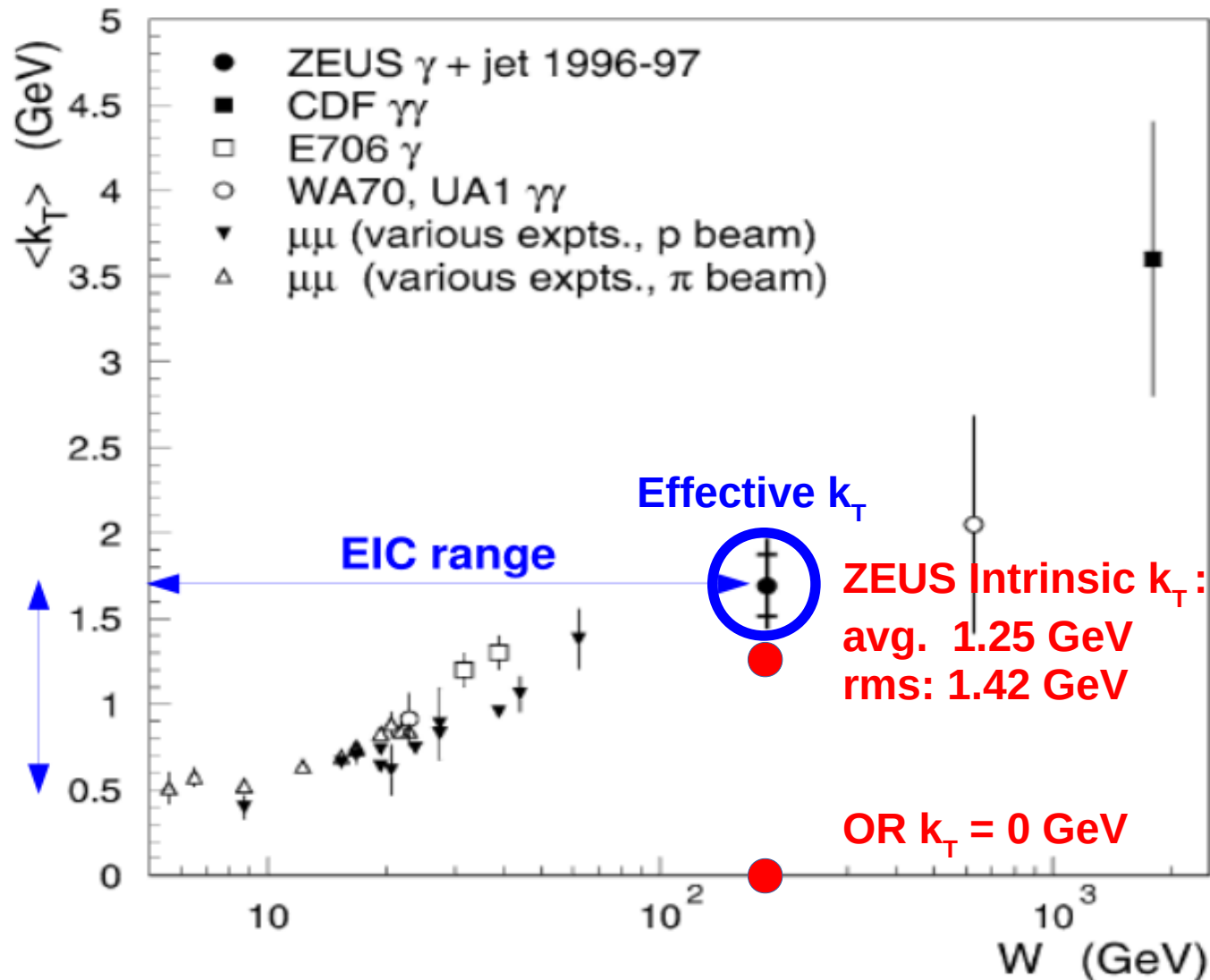
“Any shortfall in [parton] shower activity ... has to be compensated by the Primordial  $k_T$  source, which thereby largely loses its original meaning.”

ZEUS Collaboration / Physics Letters B 511 (2001) 19–32



# Running of effective $k_T$

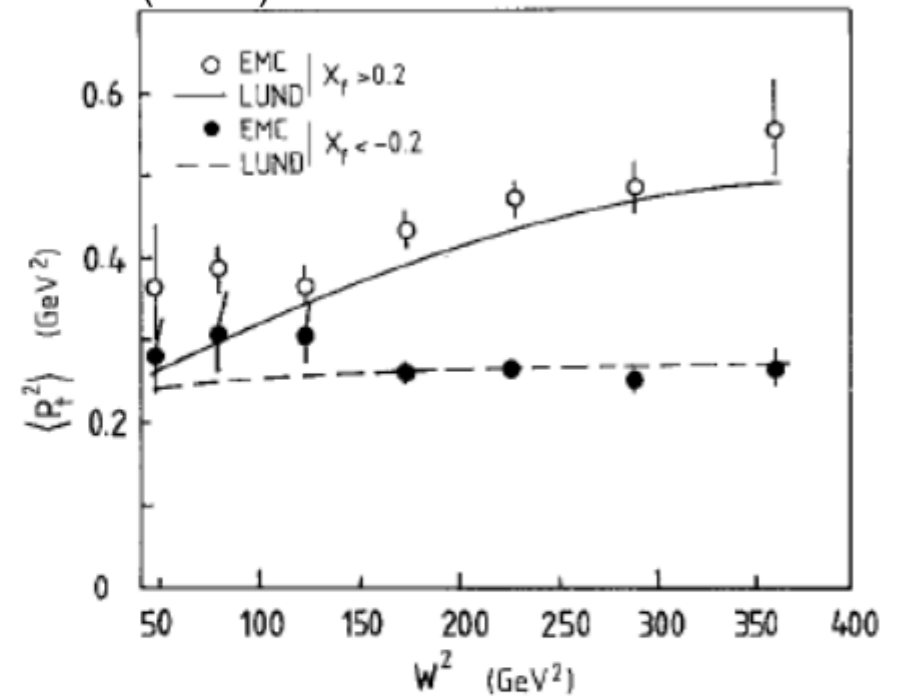
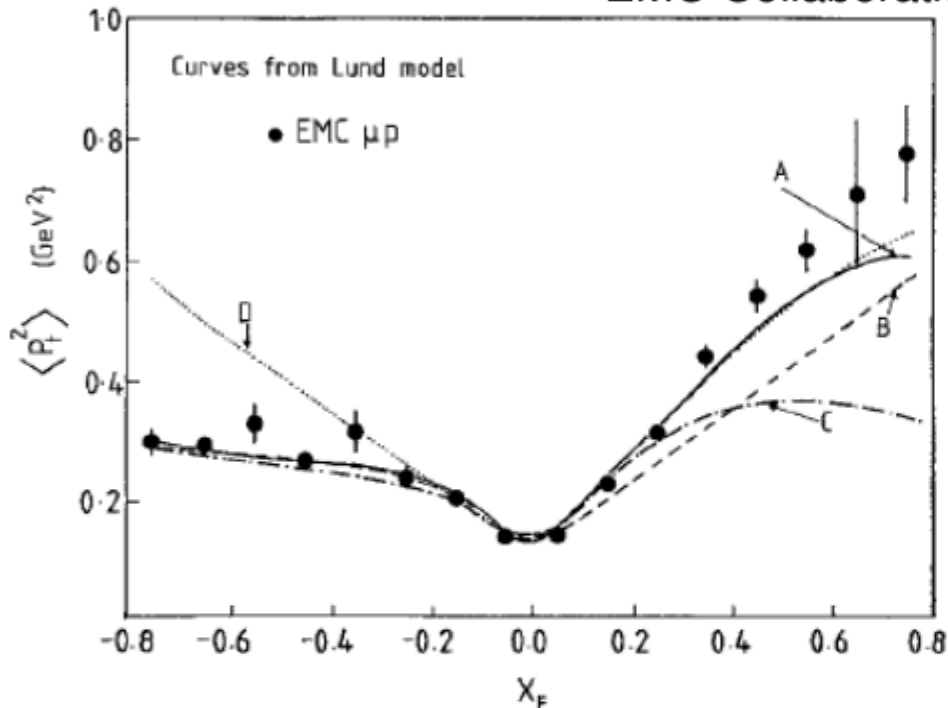
*ZEUS Collaboration / Physics Letters B 511 (2001) 19–32*



ZEUS  $k_T$  total = 1.69 GeV is 1.25 GeV (intrinsic) + parton shower using Pythia 6.1  
 OR 0 (intrinsic) + ~1.9 GeV parton shower using HERWIG

# EMC saw no $W^2$ dependence for $\langle p_T^2 \rangle$

EMC Collaboration, ZPC 36 (1987) 527



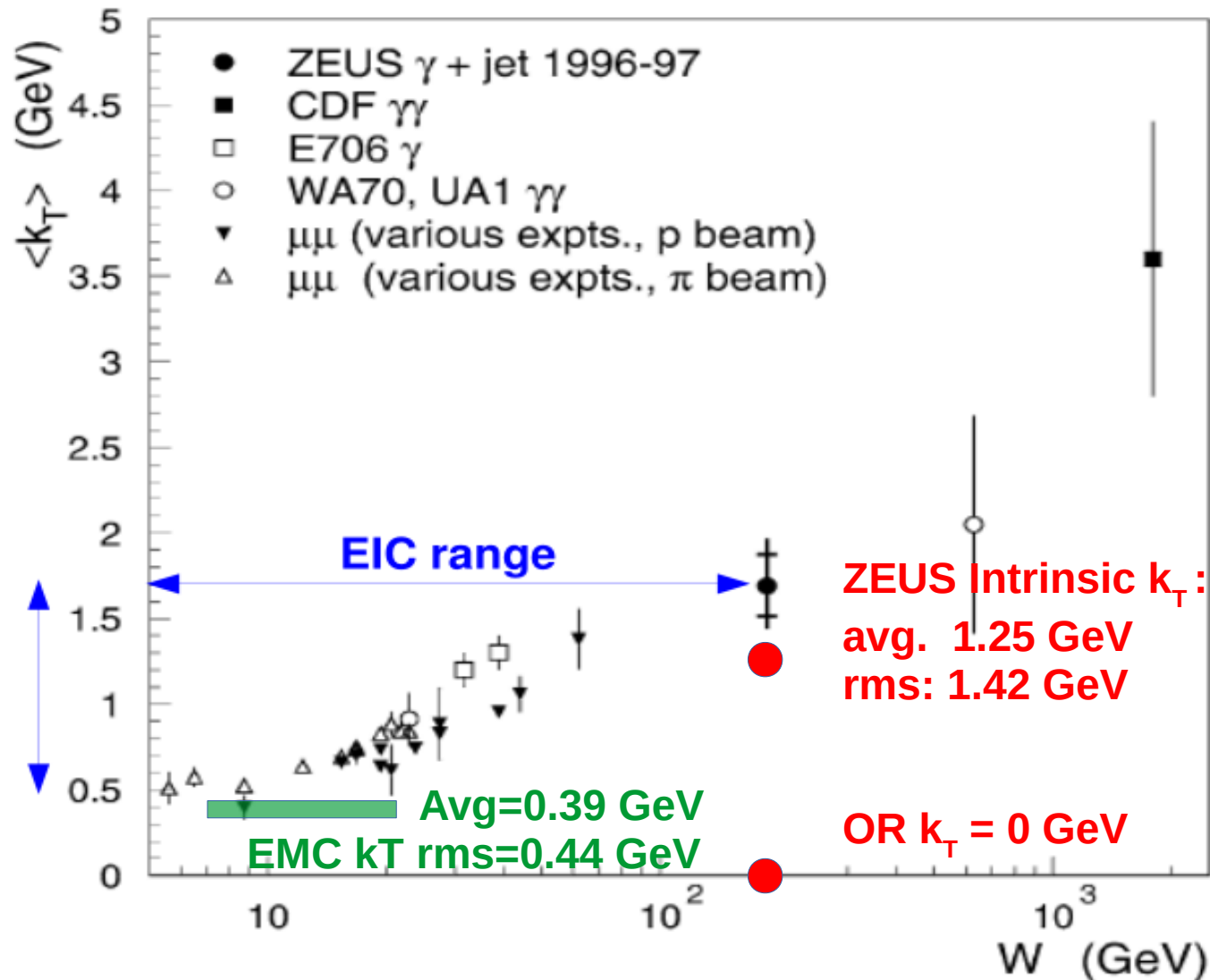
**EMC kinematics:**

**280 GeV  $\mu p$  Fixed Target**

**$Q^2 > 4 \text{ GeV}^2$        $4 < W < 20 \text{ GeV}$**

# Running of effective $k_T$

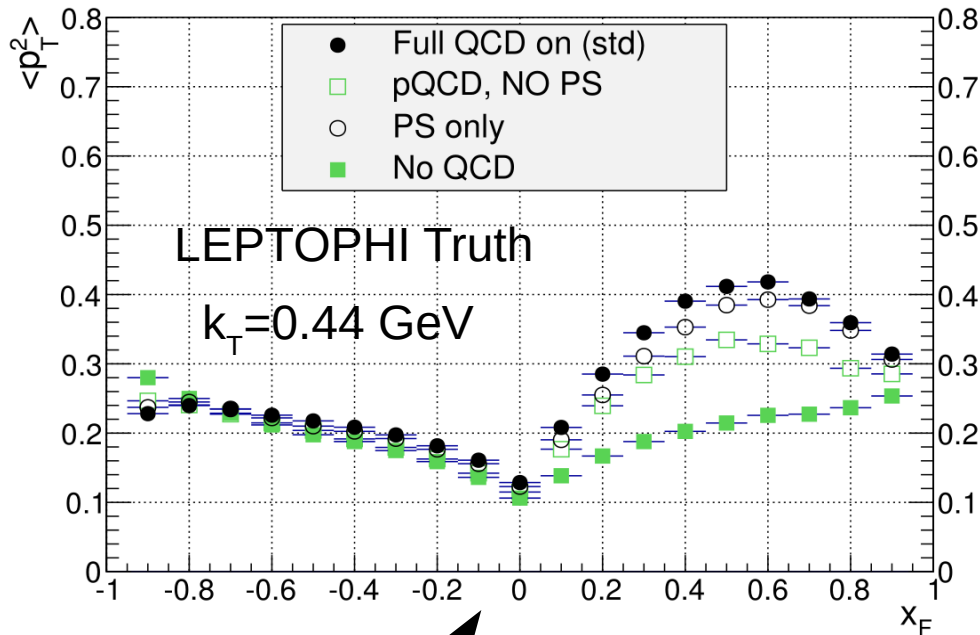
*ZEUS Collaboration / Physics Letters B 511 (2001) 19–32*



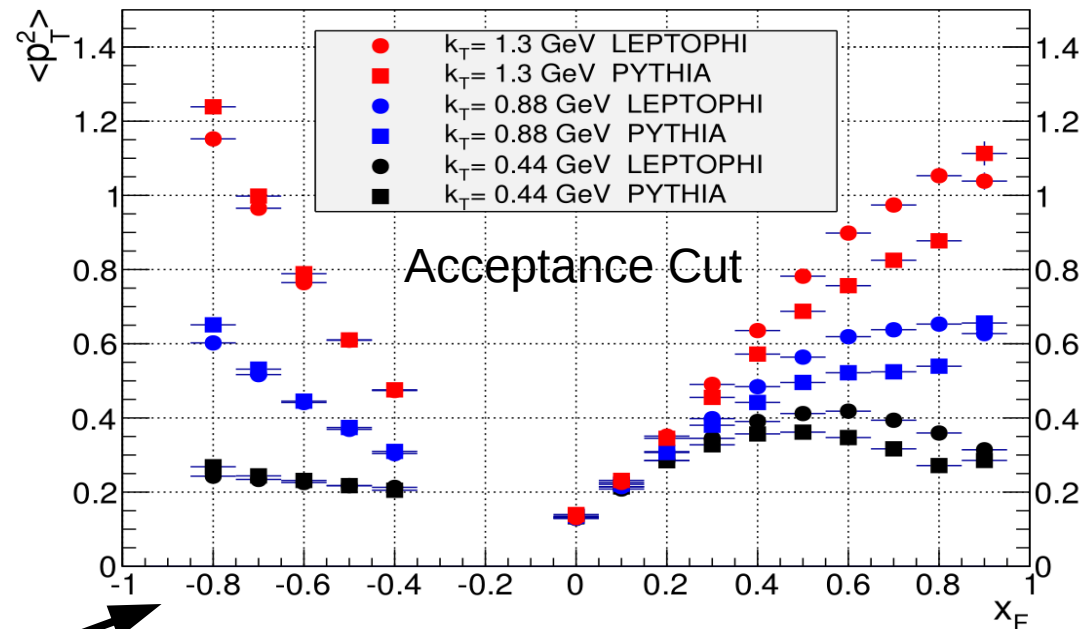
ZEUS  $k_T$  total = 1.69 GeV is 1.25 GeV (intrinsic) + parton shower using Pythia 6.1  
 OR 0 (intrinsic) + ~1.9 GeV parton shower using HERWIG

# For ep, we can measure $k_T$ at EIC

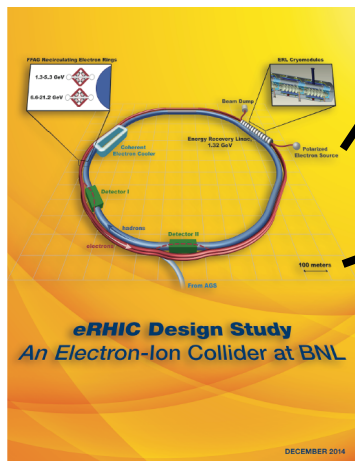
$\pi^+, K^+, p$   $Q^2 > 1.0 \text{ GeV}^2$  15x100 ep ideal detector



$\pi^+, K^+, p$   $Q^2 > 1.0 \text{ GeV}^2$  15x100 ep EIC det. acceptance



LEPTOPHI based on LEPTO 6.5.1  
PYTHIA is EIC modified PYTHIA 6.4



Detector Requirements @ EIC:

Measure  $p$  (or  $E$ ) & charge to  $\eta$  of 5  
+ Roman Pots for very forward protons

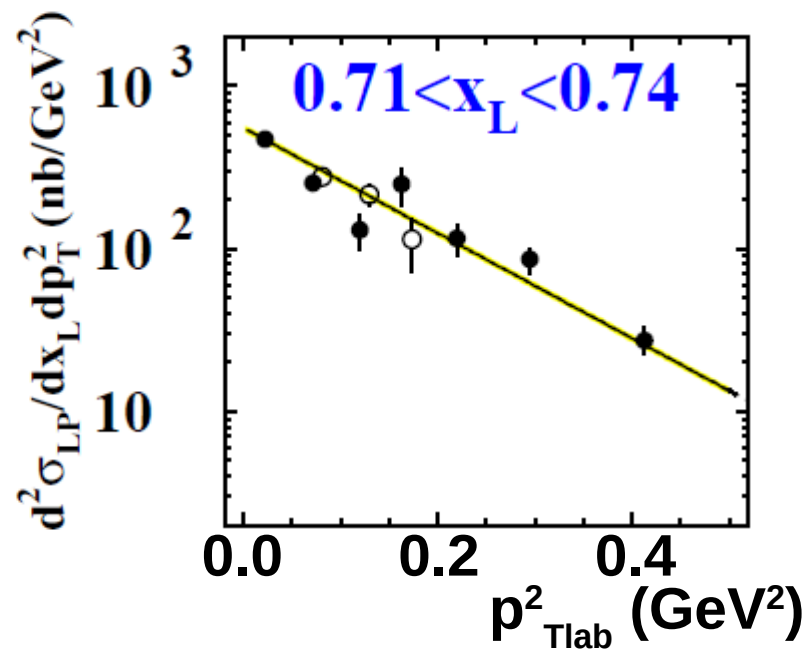
# Intrinsic $k_T$ summary

- Intrinsic  $k_T$  of struck parton:
  - Is reflected in the target remnant as well as struck parton (both forward and negative  $x_F$ )
  - Impacts hadron  $p_T$  like  $|x_F| k_T$
- Dynamical  $p_T$  from soft or hard QCD shows up primarily forward ( $\gamma^*$  direction in hadronic cm)
- Therefore intrinsic  $k_T$  cleanest at  $x_F < -0.2$

# ZEUS used lab variables

ZEUS kinematics:  
 27.5 x 820 GeV  $e^+p$   
 $Q^2 > 3 \text{ GeV}^2$   
 $45 < W < 225 \text{ GeV}$

ZEUS, JHEP 06 (2009) 074

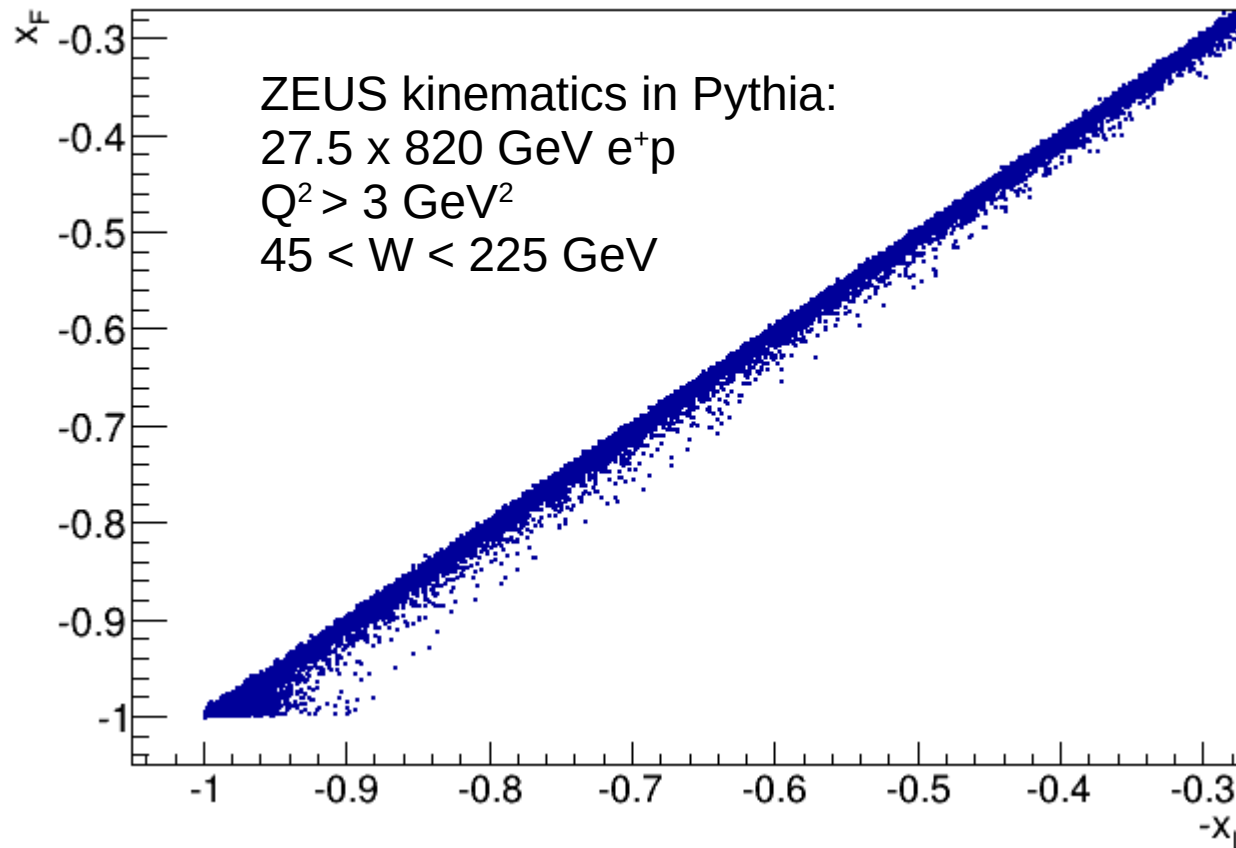


- ZEUS LPS s123 4.8 pb<sup>-1</sup>
- ZEUS LPS s456 12.8 pb<sup>-1</sup>
- $Q^2 > 3 \text{ GeV}^2, 45 < W < 225 \text{ GeV}$
- Fit  $A \cdot e^{(-b \cdot p_T^2)}$

$p_{Tlab}$

$x_L \equiv p_z / P_{zbeam(p)}$

# Comparing lab frame and HCMS



## Lab vs. HCMS

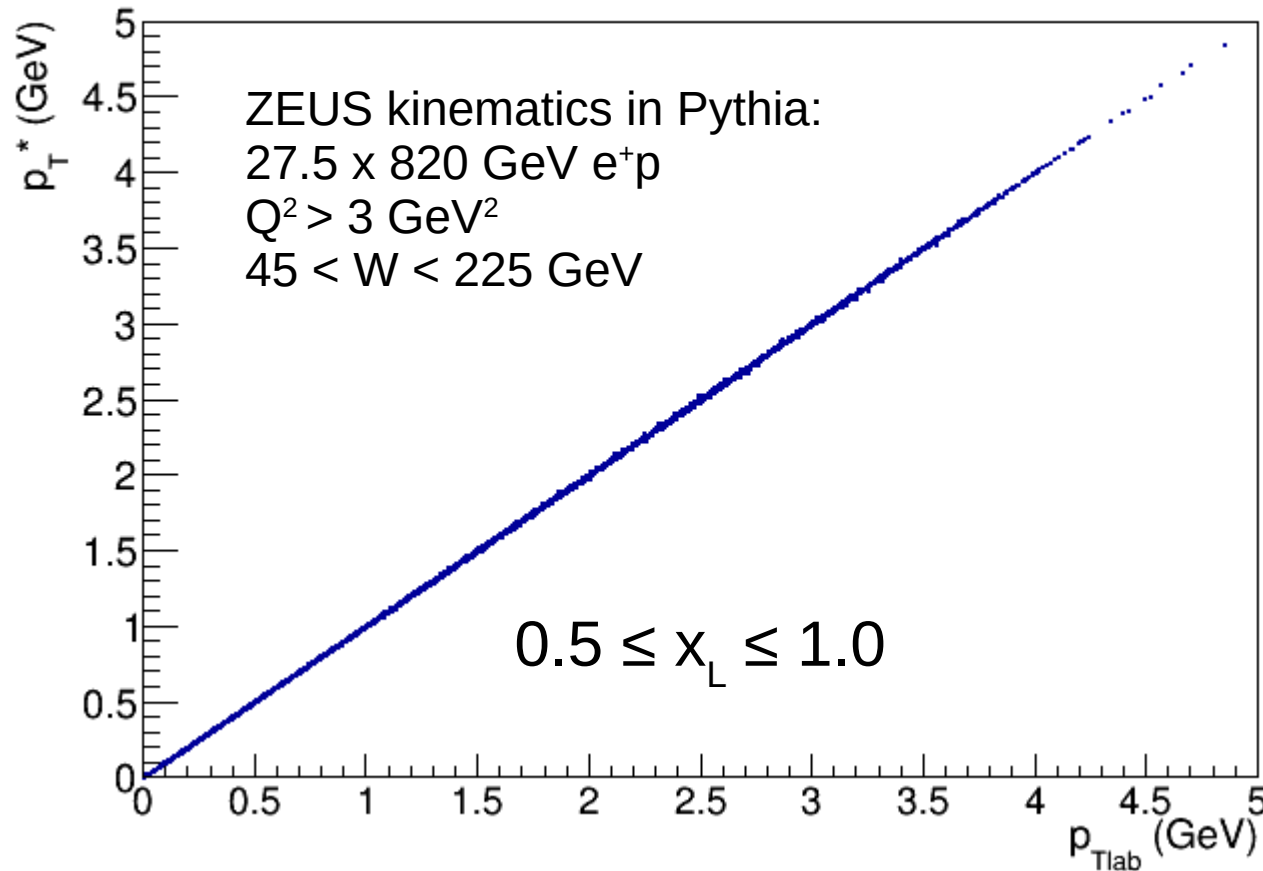
$$x_L \equiv p_z / P_{z\text{beam}}(p) \sim -x_F$$

$$E_{\text{beam}}(e) \ll E_{\text{beam}}(p),$$

$$q^\mu \ll P^\mu \text{ in lab}$$

Lab is almost a “fixed  $\gamma^*$ ” frame instead of a “fixed target” frame.  
 $x_L = -x_F$  for  $x_F < -0.2$  in fixed lepton.  $x_F = z \equiv E_h/\nu$  for  $x_F > 0.2$  in fixed target.

# Comparing lab frame and HCMS



## Lab vs. HCMS

$$p_{\text{Tlab}} \sim p_T^*$$

$$E_{\text{beam}}(e) \ll E_{\text{beam}}(p),$$

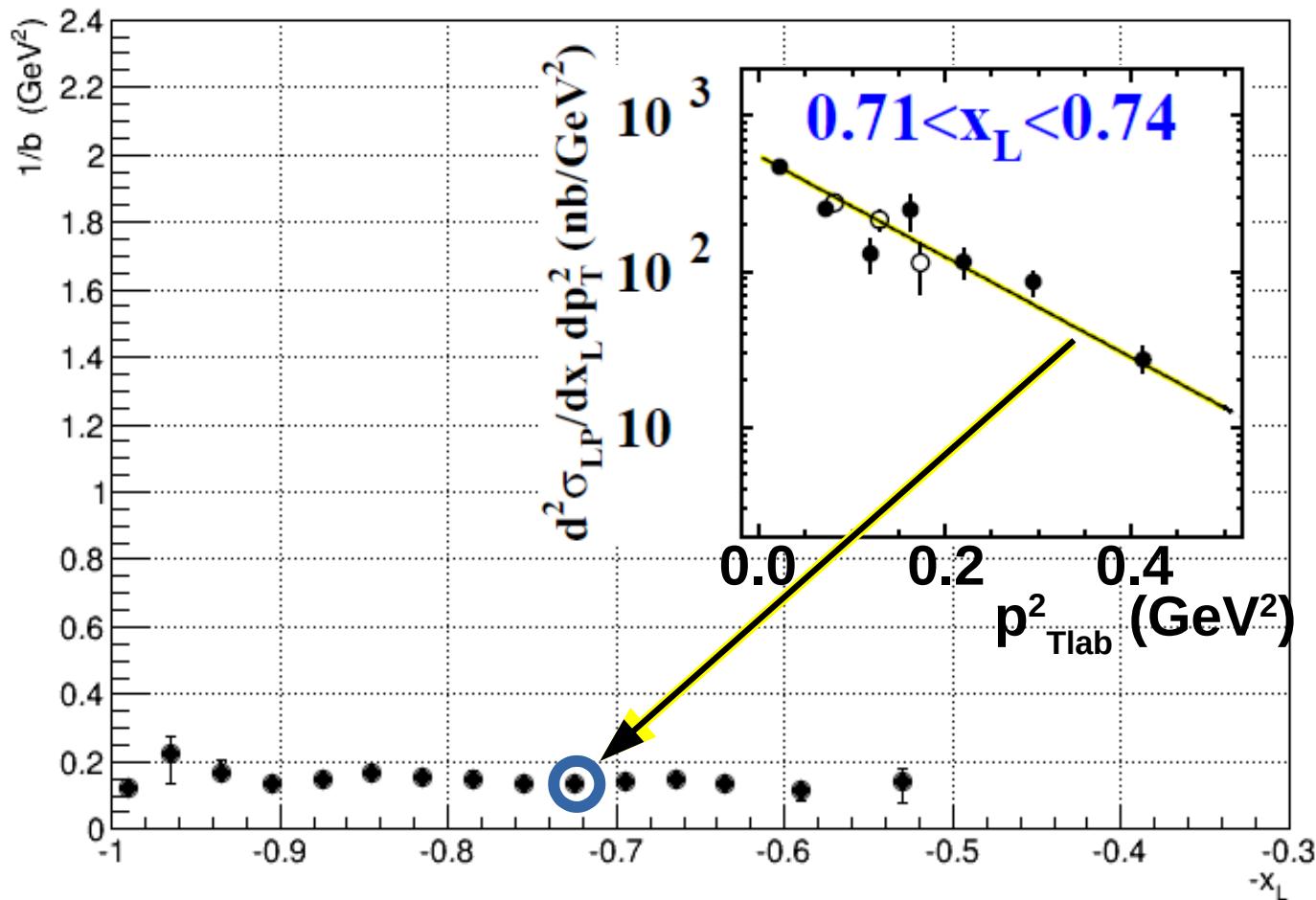
$$q^\mu \ll P^\mu \text{ in lab}$$

Empirically,  $p_{\text{Tlab}}$  (wrt beam) also matches  $p_T^*$  (HCMS wrt  $\gamma^*$ )!

# Laboratory “seagull” from ZEUS fits

ZEUS  $1/b$  vs.  $-x_L$

ZEUS, JHEP 06 (2009) 074



- ZEUS LPS s123 4.8 pb<sup>-1</sup>
- ZEUS LPS s456 12.8 pb<sup>-1</sup>
- $Q^2 > 3$  GeV<sup>2</sup>,  $45 < W < 225$  GeV
- == Fit  $A \cdot e^{(-b \cdot p_T^2)}$

$\langle p_T^2 \rangle = 1/b$  from fit

$x_F \approx -x_L$

# EIC/BNL Pythia 6.4.28 version

Non-trivial beam remnant clusters fragment into diquark+meson or baryon+quark. The  $p_L$  fraction carried by baryon/diquark is called  $\chi$ .

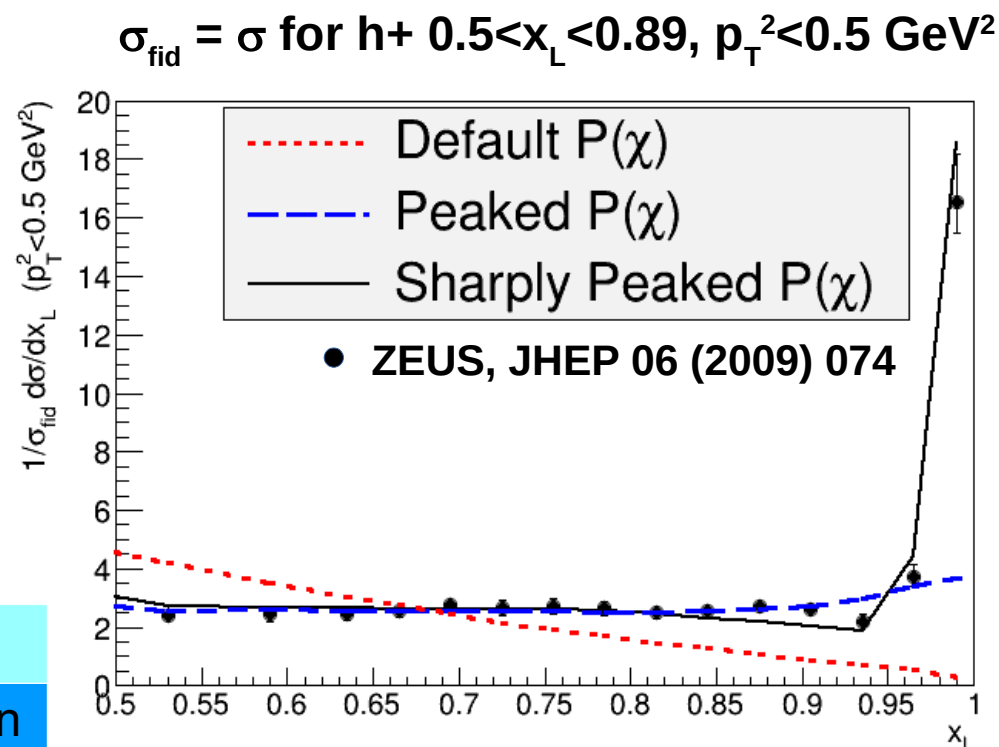
We modified Pythia to split the  $k_T$ -recoil using the same  $\chi$ , as is done in LEPTO/PEPSI.

Additionally we tuned  $P(\chi)$  to match ZEUS data. Used “sharply peaked” for ZEUS comparisons.

	MSTP(94)	PARP(97)	$P(\chi)$
Default	3	-	Frag. function
Peaked	2	9	$10(1-\chi)^9$
Sharply	2	75	$76(1-\chi)^{75}$

08-January-2016

MDB - Actually Measuring  $k_T$

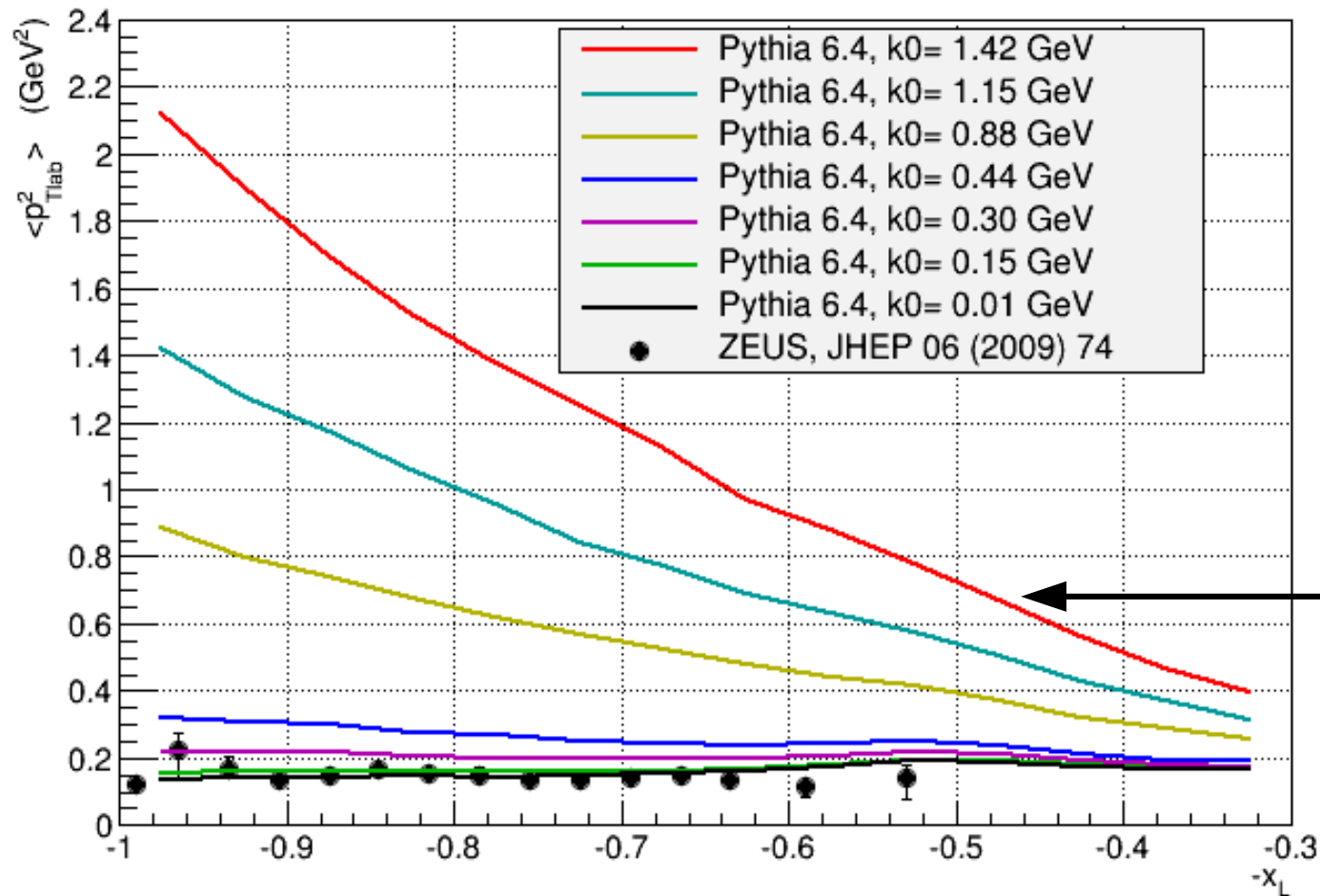


**NOTE: Seagull plot is NOT strongly affected by  $P(\chi)$ .**

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# Laboratory “seagull” from ZEUS

ZEUS  $1/b$  vs.  $-x_L$



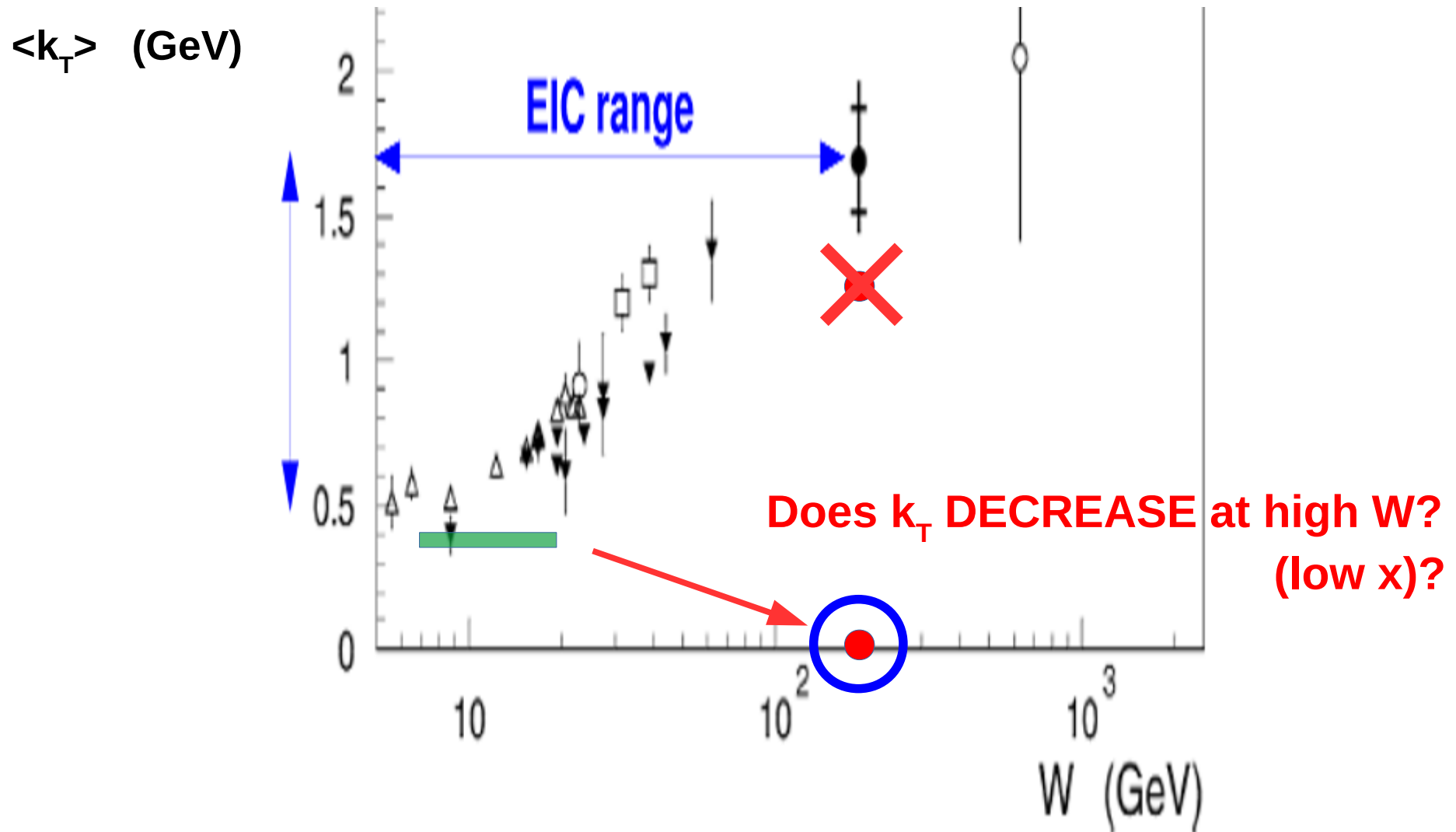
Pythia 6.4.28  
EIC/BNL version

$k_0 = k_T^{\text{rms}} = \text{PARP}(91)$

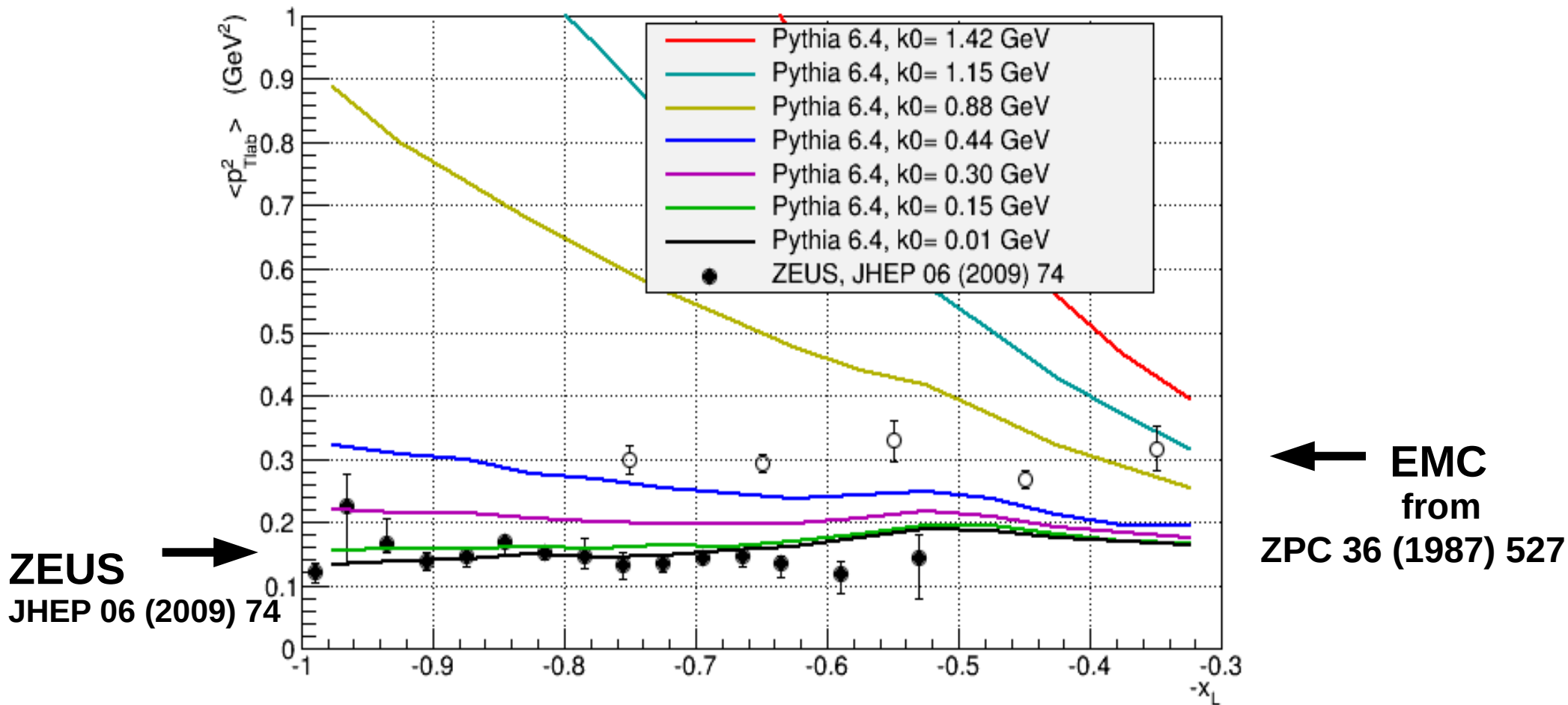
**$k_0 \neq 1.42$  GeV**

**$k_0 \approx 0.01$  GeV**

# Running of **actual** $k_T$



# Hadron $\langle p_T^2 \rangle$ : ZEUS = $\frac{1}{2}$ EMC

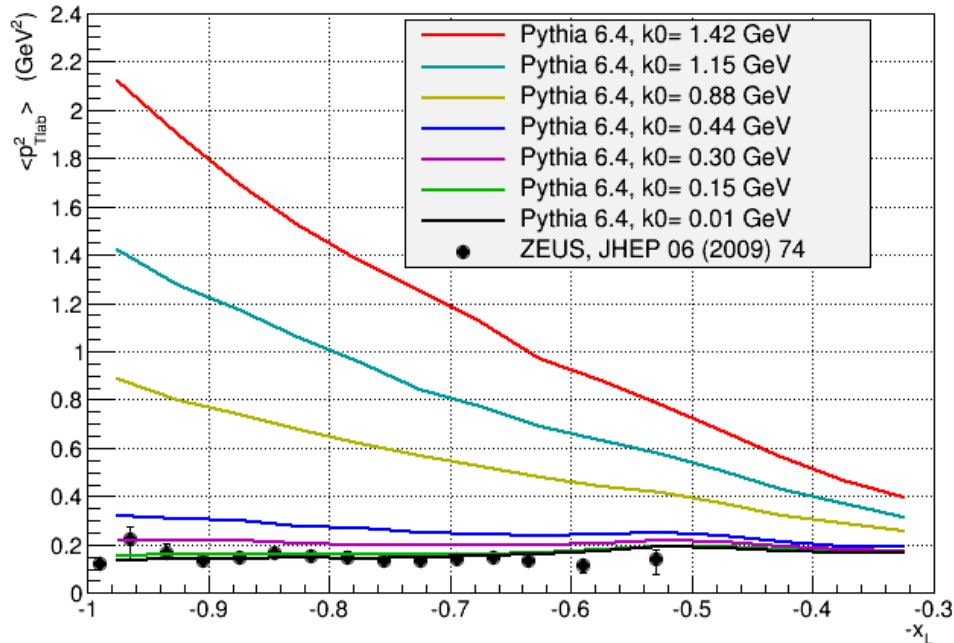


# What is happening?

- Intrinsic  $k_T$  could actually depend on  $W$  (or  $x_{Bj}$ )
  - Sea vs. valence quarks vs. gluons
- Non-gaussian tails could cause the discrepancy due to limited ZEUS acceptance.
- Fragmentation (and cluster breakup)  $p_T$  could depend on  $W(?)$
- EIC can resolve this!
  - Extended range in beam energy and  $(x, Q^2)$
  - Flavor-tagging events
  - Correlations to distinguish fragmentation  $p_T$  &  $k_T$

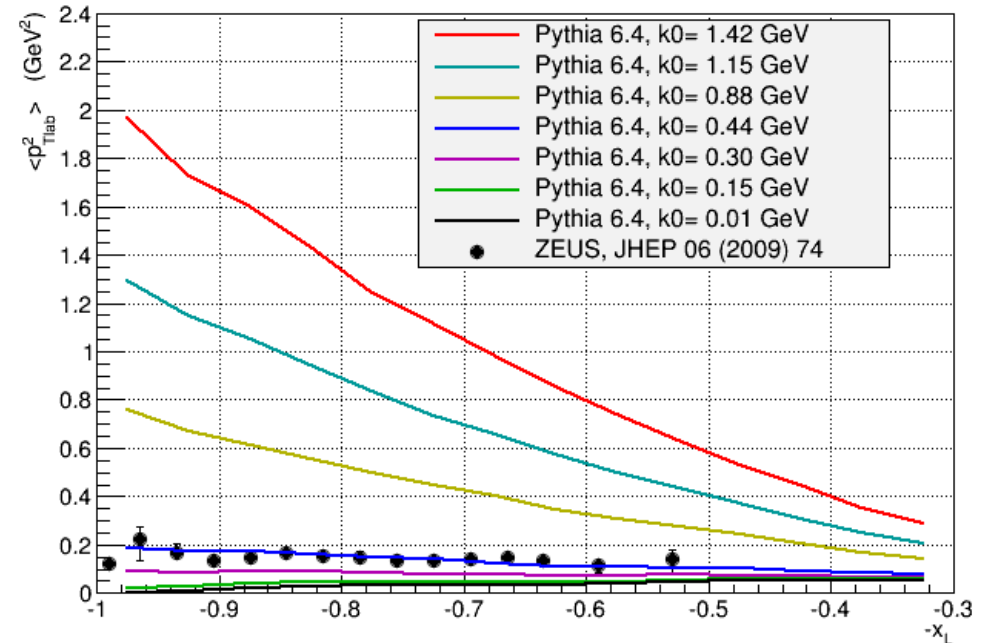
# Fragmentation $p_T$ vs intrinsic $k_T$

ZEUS 1/b vs.  $-x_L$



PARJ(21)=0.36 GeV (default) =  
Fragmentation  $p_T$  AND  
Beam remnant cluster breakup  $p_T$   
Data favors  $k_0$ =PARP(91)=0.01 GeV

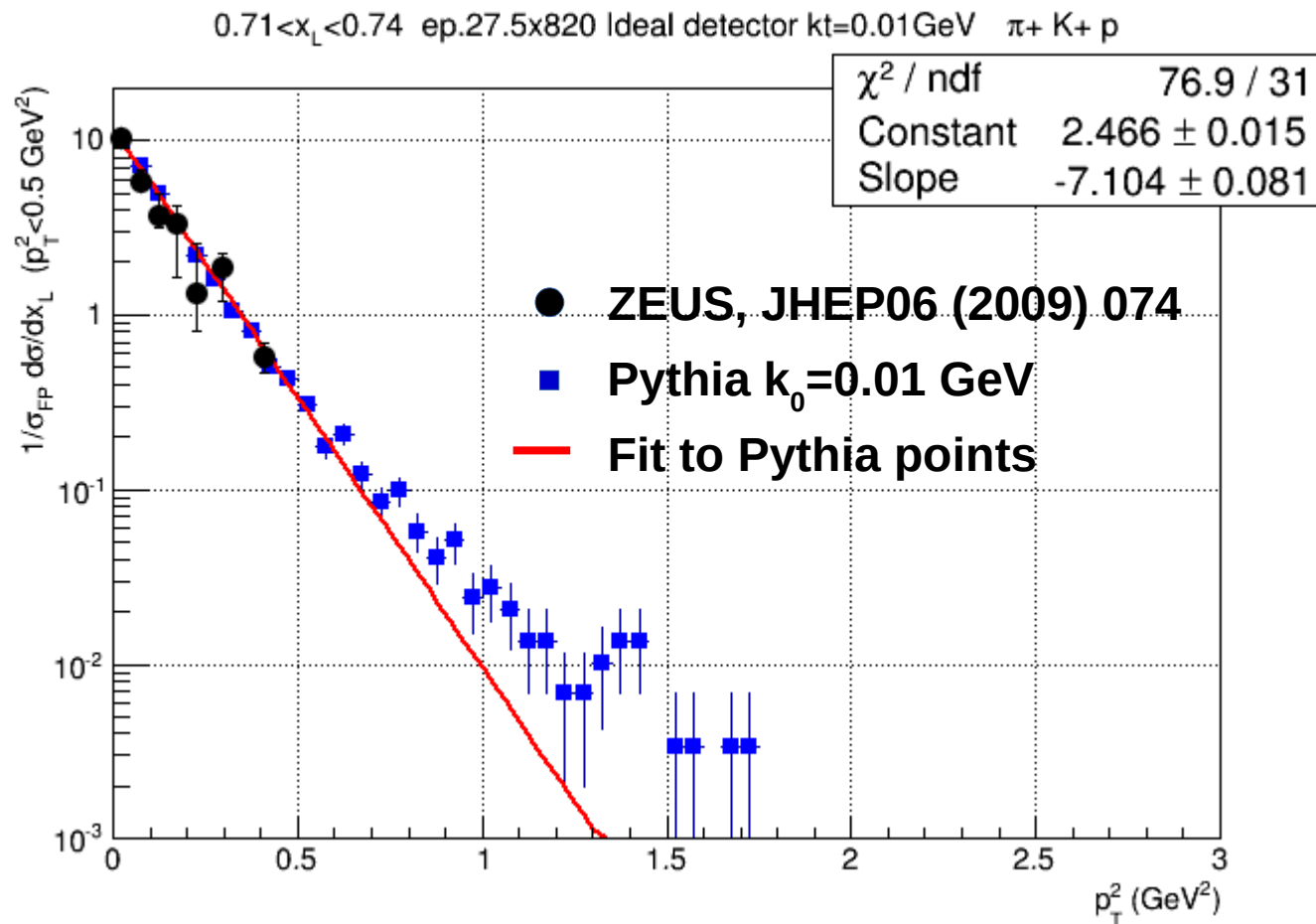
ZEUS 1/b vs.  $-x_L$



PARJ(21)=0.01 GeV (TINY!) =  
Fragmentation  $p_T$  AND  
Beam remnant cluster breakup  $p_T$   
Data favors  $k_0$ =PARP(91)=0.44 GeV

**But fragmentation decreasing with  $W$  is weirder than  $k_T$  decreasing with  $W$**

# ZEUS's acceptance is limited

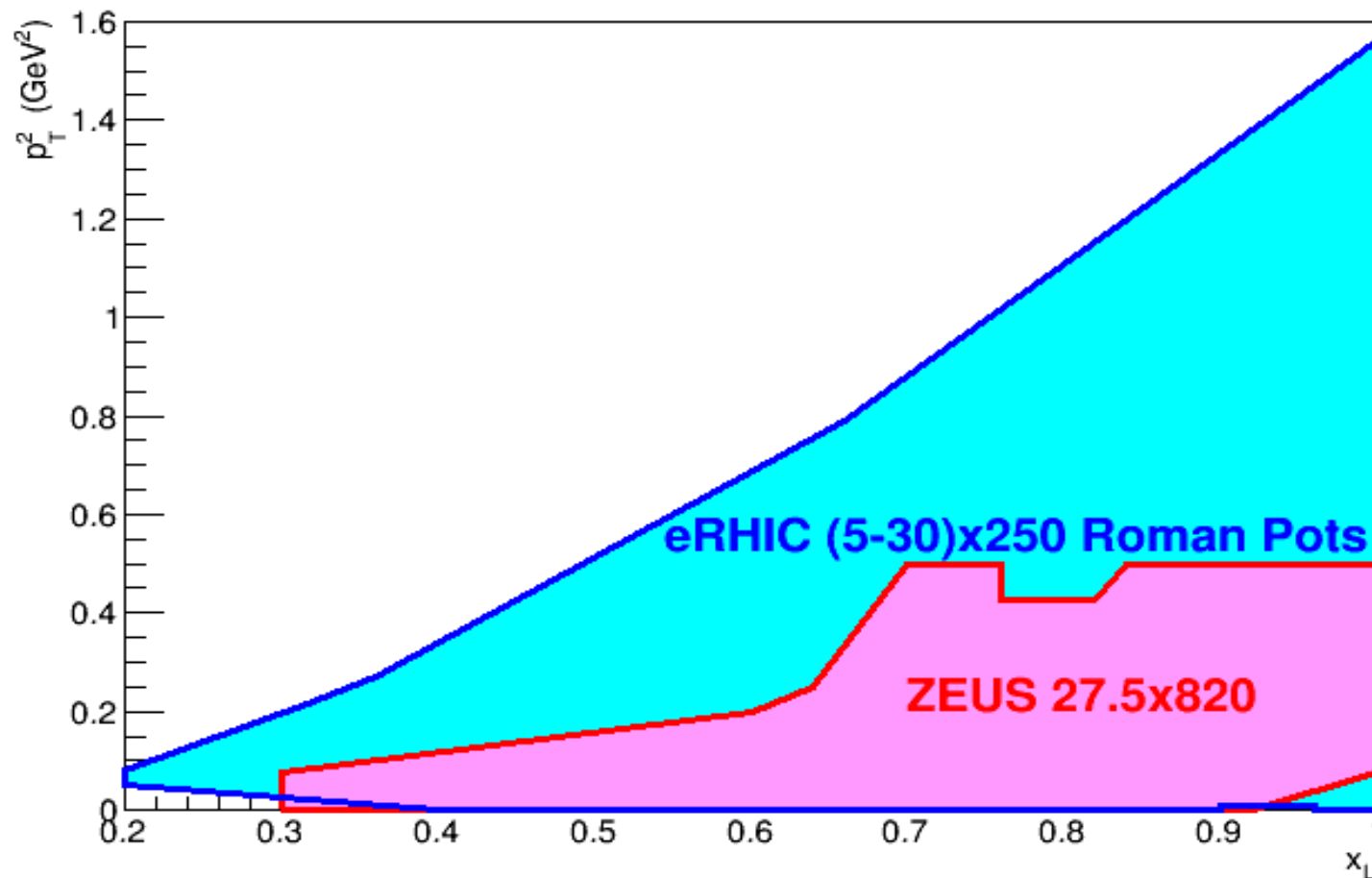


EMC used a streamer chamber and a fixed target – nearly complete acceptance.

Non-gaussian tails  
 For  $p_T^2 > 0.5 \text{ GeV}^2$   
 could explain  
 $k_T(\text{ZEUS}) < k_T(\text{EMC})$

# EIC acceptance better (250 GeV)

Forward Acceptance



Thanks to Richard Petti (BNL) for the Roman Pot simulation

# Summary

- **We can actually measure  $k_T$  in ep**
  - Beam remnant jet recoil: a golden measurement?
- ZEUS data:
  - **Intrinsic  $k_T \sim 0$  GeV and certainly not 1.42 GeV**
  - Assuming gaussian  $k_T$  and  $p_{T\text{frag}}(W)$  constant
- EIC needed to settle open questions
  - Non-gaussian tails?
  - $x_{Bj}$  and/or flavor dependence
  - Fragmentation  $p_T$  vs. intrinsic  $k_T$  using correlations

# Backup Slides

# The Pythia 6 Manual describes the problem nicely

“It is customary to assign a primordial transverse momentum to ... take into account the motion of the quarks inside the original hadron..”.

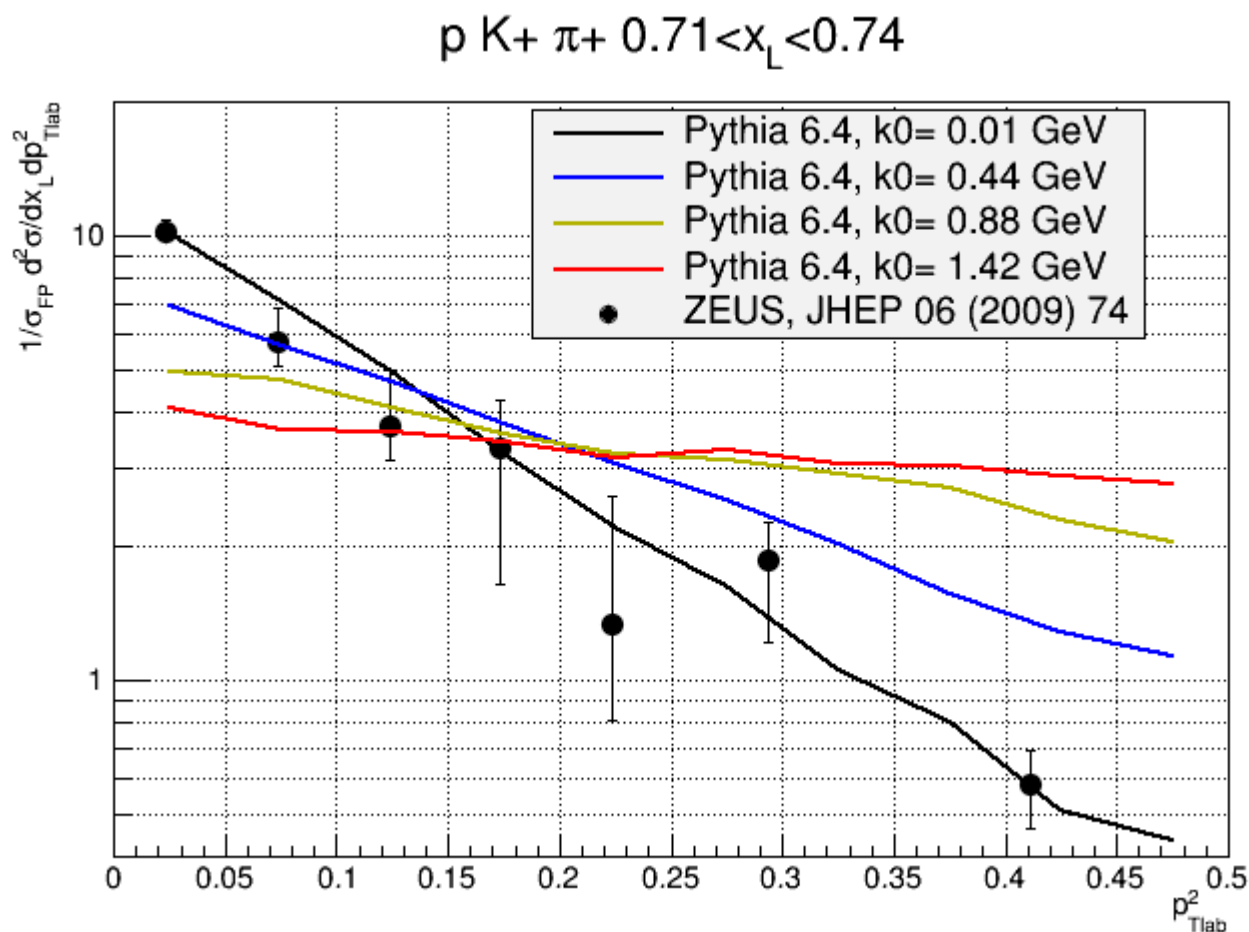
“A number of order ... 300 MeV could therefore be expected. However in hadronic collisions much higher numbers than that are often required to describe the data ... 1GeV [or] 2 GeV.”

“Any shortfall in [parton] shower activity ... has to be compensated by the Primordial  $k_T$  source, which thereby largely loses its original meaning.”

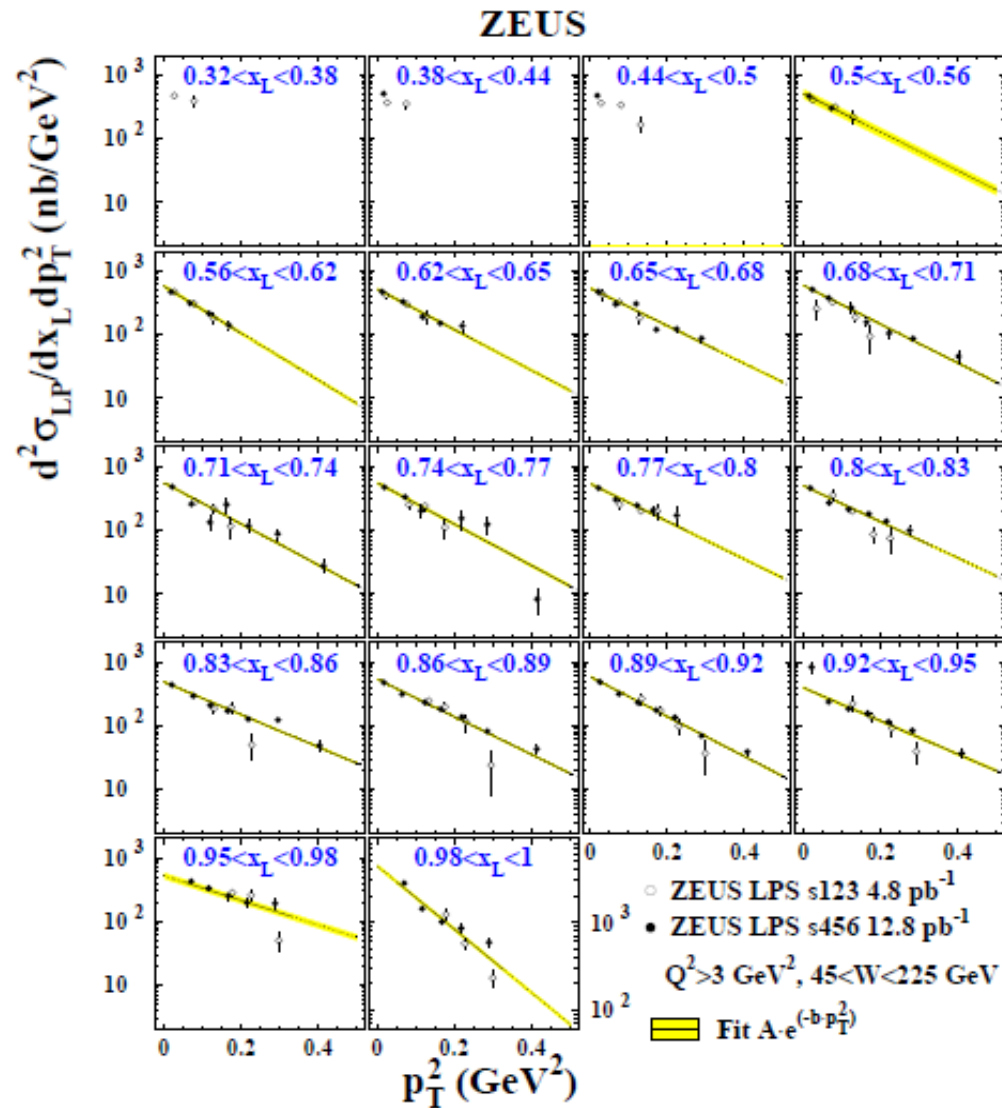
Pythia 6.4 manual [hep-ph/0603175](http://hep-ph/0603175)

In order to relate  $k_T$  to fundamentals like  $Q_s$ :  
We must actually measure  $k_T$ !

# Example 2d slice.

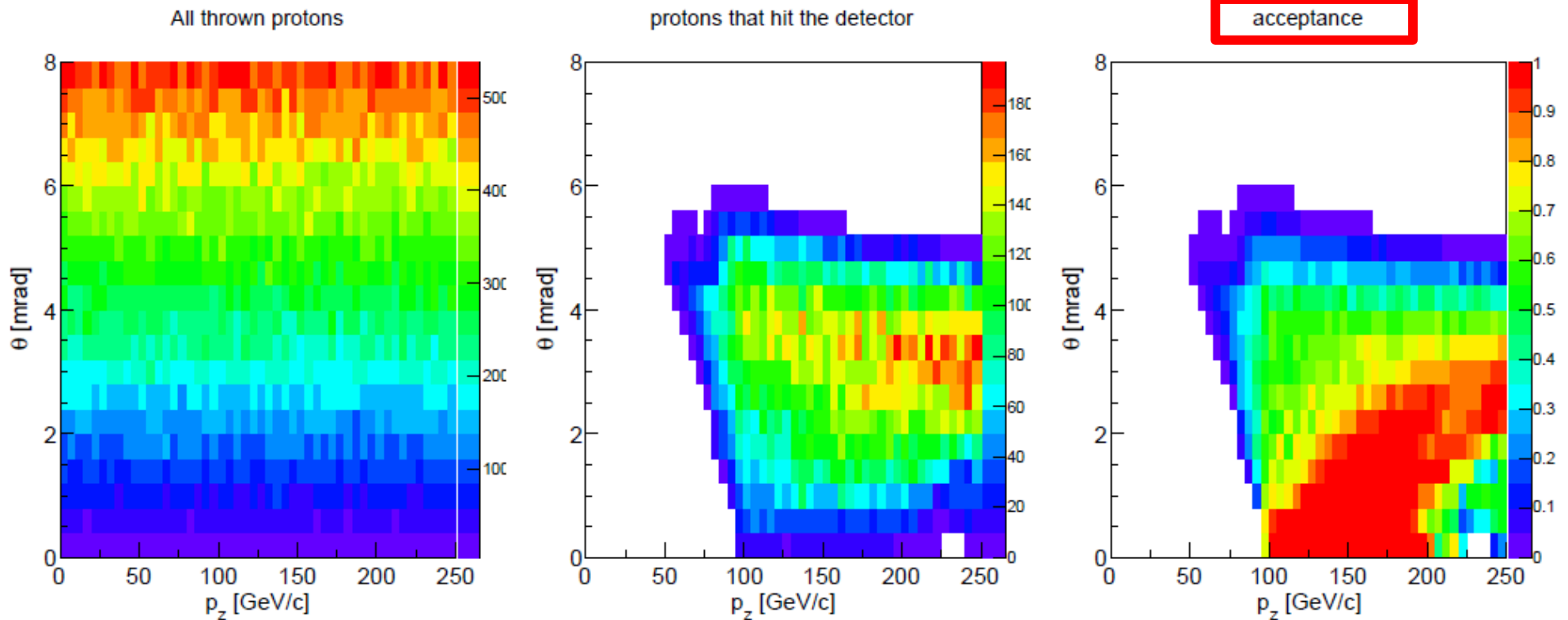


# ZEUS 2D data



# Roman Pots at eRHIC

By Richard Petti (BNL)



$$p_T^2 = (p_z \tan \theta)^2$$

$$x_L = p_z / P_{z\text{beam}}$$

# Can we use this for eA?

Um... Maybe. But it's complicated.

For eA in the saturation regime,  
the  $k_T$  recoil will be shared  
between multiple nucleons

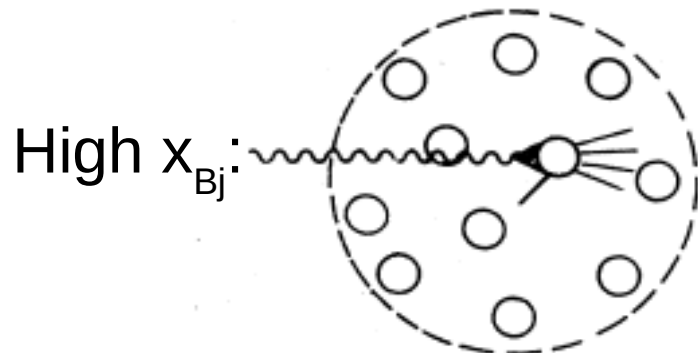
That's a whole other talk:

[https://wiki.bnl.gov/conferences/images/8/85/MDBAKER\\_2015-07-09-DPMJetHybrid2.pdf](https://wiki.bnl.gov/conferences/images/8/85/MDBAKER_2015-07-09-DPMJetHybrid2.pdf)

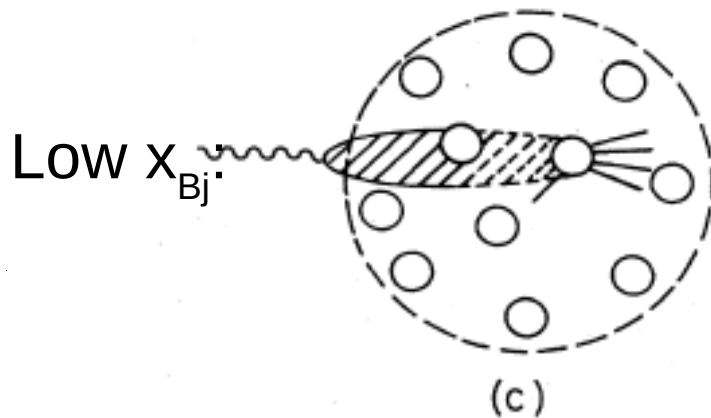
# eA: Basic Quantum Mechanics

$$\hbar=c=1 \quad r=0.88 \text{ fm} \quad 1/(2Mr) = 0.12 \quad \Delta p_z \Delta z = 1/2$$

Bauer, Spital, Yennie, Pipkin  
Rev. Mod. Phys. 50 (1978) 261



Nucleus Rest Frame (b)



(c)

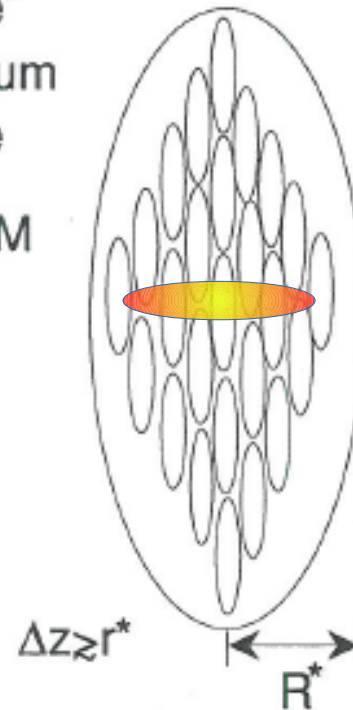
$$\lambda_h/r \approx 1/(2Mr) = 0.12/x_{Bj}$$

"Infinite"  
Momentum  
Frame

$$\gamma = P/M$$

$$r^* = r/\gamma$$

$$R^* = R/\gamma$$



$$p_z^{\text{quark}} = Mx\gamma$$

$$\Delta z = 1/(2Mx\gamma)$$

$$\Delta z/r^* = 1/(2Mxr) = 0.12/x_{Bj}$$

**For  $x_{Bj} \ll 0.12$ , parton wavefunctions and/or interaction cannot be localized.**